Electromagnetic Dissociation and Space Radiation

John W. Norbury

Physics Dept., Worcester Polytechnic Institute, Worcester, Massachusetts, 01609, USA

Khin Maung Maung

Physics Dept., Hampton University, Hampton, Virginia, 23668, USA

Abstract

Relativistic nucleus-nucleus reactions occur mainly through the Strong or Electromagnetic (EM) interactions. Transport codes often neglect the latter. This work shows the importance of including EM interactions for space radiation applications.

1 Introduction

When astronauts travel into space they receive a significant dose of radiation because they are no longer protected by the Earth's atmosphere and magnetic field. This radiation comes from three different sources, namely from geomagnetically trapped electrons and protons (Van Allen radiation belts), from solar energetic particles (mainly protons) and from Galactic cosmic rays (protons and heavier nuclei) emitted by stellar wind and flares and accelerated by supernova shock waves. The solar particles are particularly dangerous during times of solar flares and coronal mass ejections.

A typical medical x-ray delivers a dose of about 0.1 mSv. The natural background radiation in the United States is about 4 mSv/year. The International Commission on Radiological Protection (ICRP) [1] has set a recommended upper limit of an additional 1 mSv/year for the general public. The ICRP recommended upper limit for radiation workers [1] is 20 mSv/year and for astronauts the recommended limit [2] is 500 mSv/year. Currently astronauts on the International Space Station (ISS) receive a dose of about 150 mSv/year, which is well below the maximum limit. However it has been estimated [3] that the dose received on a Mars mission in a conventional spacecraft will be about 1000 mSv/year which is double the recommended limit for astronauts. The ISS is in a low Earth orbit with an average height of only 400 km above Earth's surface and most of the orbit occurs at relatively low latitude (low orbital inclination). Thus ISS still receives a significant amount of radiation protection from Earth's magnetic field. Most of the dose received on ISS comes from traversal of the South Atlantic Anomaly and also during times when the orbit is at high inclination. The significant extra dose of radiation that will be received on a Mars or Lunar mission is due to the absence of a significant magnetic shield.

NASA has recently initiated a new program leading to human exploration of the Moon and Mars. Such long-term human missions will result in astronauts being exposed to the

largest dose of space radiation ever experienced. There is a great need to provide accurate estimates of crew exposure to this radiation.

A typical space radiation transport code works as follows. The radiation environment outside the spacecraft needs to be simulated. This is done by using mathematical representations of the spectrum (i.e. number of particles versus energy) for the various particles, such as electrons, protons, heavy ions etc. Of course the cosmic ray spectrum is time dependent (especially as a function of solar cycle) and also varies depending on location in the solar system. These factors are also included by some mathematical function. The spacecraft shield material (typically Aluminum) is also specified. The incident spectra are fed into the Boltzmann transport equation, which takes the input spectrum, and converts it to an output spectrum, after radiation transport through the spacecraft material. From the output spectrum one can then determine the radiation dose. Of course, for a Mars mission, one must also include transport through the Martian atmosphere, just as one must include transport through Earth's atmosphere, when calculating radiation doses experienced by high flying aircraft [10]. The particles in the cosmic ray spectrum undergo atomic and nuclear interactions with the particles in the shield material. These interactions are specified as atomic or nuclear interaction *cross sections*. Thus the fundamental inputs to the Boltzmann equation are the incident cosmic ray spectrum and the particle interaction cross sections. Once these are specified the Boltzmann equation can then be solved numerically either with deterministic or Monte Carlo methods [3].

When one goes to the dentist, a lead (Pb) apron is donned during an x-ray. One might think that heavy materials such as Pb are good generic radiation shield materials. Pb is certainly good for x-rays and electrons, but is very poor for protection against the more complex cosmic rays spectrum which consists of protons and heavy nuclei. These nuclei interact with the Pb nuclei and because both projectile and target are complex nuclei, there are many nuclear reactions which occur. In fact a *small* amount of Pb shield produces an increase, rather than a decrease in the radiation that an astronaut receives. The same is true for the Aluminum (Al) shields [3] from which spacecraft have traditionally been made. One needs a *lot* of Al in order to provide adequate shielding. Lighter nuclei, such as hydrogen (H) or carbon (C) are much more effective for shielding from cosmic radiation. From another point of view, aerospace engineers would always prefer to construct aircraft and spacecraft out of light materials, in order to reduce heavy lift requirements. Thus it is indeed fortunate that light materials provide the best protection against space radiation. This has been one of the major discoveries of the space radiation group at NASA Langley Research Center [3].

Most of the steady dose received on a Mars mission will come from radiation due to Galactic Cosmic Rays. There will also be transient periods of high dose during times of intense solar activity. The Galactic Cosmic Rays are composed [11] of about 98% nuclei and 2% electrons and positrons. The nuclear component comprises about 87% protons, about 12% alpha particles and about 1% heavier nuclei. Even though the heavy nuclei are not very abundant, they nevertheless contribute a large amount to the radiation dose

because this depends on Z^2 where Z is the charge of the nucleus. The iron nucleus (Fe), being the most tightly bound of all atomic nuclei, is the most abundant of the heavy nuclei in the cosmic ray spectrum and contributes a significant amount to the total dose. The number of nuclei heavier than Fe drops off very rapidly, and are therefore of less importance.

The peak of the proton and heavier ion flux in the cosmic ray spectrum occurs in the energy region around 1 - 10 GeV. Fortunately this energy region is easily accessible to particle accelerators constructed over the last 50 years. This energy region is considered *intermediate energy*, with current accelerators being able to also probe much higher and lower energy regions. Thus the cross sections needed as input to the Boltzmann equation are able to be measured on Earth.

The most important nuclear reactions that occur when a cosmic ray nucleus interacts with a nucleus in a spacecraft wall are called *nucleus-nucleus collisions*. For example the incident projectile cosmic ray nucleus can be a proton or Fe nucleus and the target spacecraft nuclei are typically aluminum or light nuclei. If the projectile and target and nuclei heavier than hydrogen, the nucleus-nucleus reaction is often referred to as a *heavy-ion reaction*. The four fundamental forces observed in nature are the Strong, Weak, Electromagnetic and Gravitational forces. In a heavy ion reaction, the Weak and Gravitational forces can be neglected. The Strong force is very short range, typically acting over distance of about a *fermi* (fm $\equiv 10^{-15}$m) and dropping to zero strength at larger distances, whereas the weaker Electromagnetic (EM) force is significant over both short and long distances. At distances of the order of 1 fm the Strong force completely dominates the EM force whereas the situation is reversed at distances significantly larger than 1 fm. In a nucleus-nucleus collision, the nuclei might "crash" into each other or miss each other. When they crash into each other (i.e. come closer than 1 fm), they undergo a Strong interaction because of the small distance between them. When they miss each other (distance of closest approach larger than 1 fm), a Strong interaction will not occur, but they can still interact via the longer range EM force. One can think of a photon traveling from one nucleus to the other and causing a nuclear excitation. There are many photons with low energy, dropping off to a few photons with high energy up to some maximum cutoff. The most important photons are those with frequencies near the resonant vibration frequency of the nucleus, which result in a nuclear excitation known as the Giant Dipole Resonance (GDR) where entire nucleus undergoes large internal vibrations. The GDR decays with the emission of nucleons. Single nucleon emission is the most important, but multiple nucleon emission such, as two neutrons or alpha particles, are also significant. Nucleus-nucleus reactions occurring via the Electromagnetic (EM) force are the subject of the present paper. This reaction, with GDR excitation and subsequent nucleon emission, is called *Electromagnetic Dissociation* and is often neglected in cosmic ray transport codes. The aim of the present paper is to illustrate the importance of EMD for space radiation applications.

2 Theory of Electromagnetic Dissociation

In this section the theoretical description of EM dissociation [12, 13, 14, 15, 16, 20, 21, 22, 23, 24, 25, 31, 33] is reviewed. One can feel the influence of a moving charged particle by the field surrounding it. In the quantum mechanical picture, the moving charged particle is a source of virtual photons. The faster the particle moves, the more energetic will be the virtual photon field surrounding it. In a nucleus-nucleus collision, when the nuclei miss each other, each nucleus can feel the influence of the other by the virtual photon field. To be specific, when a projectile nucleus passes by a target nucleus, it feels the virtual photon field generated by the target, and these virtual photons can excite the projectile (via excitation of the Giant Dipole Resonance) causing the projectile to subsequently emit nucleons. (The same can also happen to the target from the photon field of the projectile.) Thus from the point of view of the projectile, it sees a beam of photons emitted from the target and responds to these photons. Thus the fundamental reaction that the projectile undergoes is a *photonuclear reaction* in which a photon is responsible for the excitation of the projectile.

The traditional photonuclear process is a single high energy photon exciting a nucleus. Thus the whole field of photonuclear physics can be imported into our description of EM dissociation. Actually in photonuclear physics it is typically an accelerated electron that provides the photons. In EM dissociation we have a nucleus, instead of an electron, providing the photons.

How many photons does the target provide and what are their energies? This is described by the virtual photon spectrum $N(E)$, where N is the number of photons with an energy E. A good description of this field is provided by the venerable Weiszacker-Williams (WW) method of virtual quanta [31], which gives the virtual photon spectrum

$$N(E) = \frac{2Z_T^2\alpha}{\pi E\beta^2}\left\{xK_0(x)K_1(x) - \frac{1}{2}\beta^2x^2\left[K_1^2(x) - K_0^2(x)\right]\right\} \tag{1}$$

where $N(E)$ is the number of virtual photons per unit energy E, Z_T is the number of protons in the target nucleus, β is the velocity of the target in units of c, and α is the Electromagnetic fine structure constant. The parameter x is defined by

$$x \equiv \frac{Eb_{\min}}{\gamma\beta\hbar c} \tag{2}$$

where $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ and $b_{\min}$ is the minimum impact parameter which is approximately equal to the sum of the nuclear radii. $K_0(x)$ and $K_1(x)$ are modified Bessel functions of the second kind.

The final EM dissociation cross section is written

$$\sigma = \int dE \, N(E)\sigma(E) \tag{3}$$

where $N(E)$ describes the virtual photon spectrum provided by the target and $\sigma(E)$ describes the response (photonuclear cross section) of the projectile to these target photons. (Again, the description can be reversed and the projectile provides photons which excite the target.)

An advantage of this Weizsacker-Williams formulation is that it is relatively easy to parameterize for use in radiation transport codes [17, 18]. Another big advantage is that *experimental* photonuclear cross sections can be used as input to equation (3). When comparing this theory to EM dissociation experiments, it is best to use such experimental photonuclear cross sections when comparing EM dissociation calculations to experiment. However this is impractical when putting EM dissociation calculations into transport codes. In that case one can use the following standard parameterizations of photonuclear cross sections

$$\sigma_{\text{abs}}(E) = \frac{\sigma_m}{1 + [(E^2 - E_{\text{GDR}}^2)^2 / E^2 \Gamma^2]} \tag{4}$$

where E_{GDR} is the energy of the peak[19] of the GDR cross section, Γ is the width of the GDR, and

$$\sigma_m = \frac{\sigma_{\text{TRK}}}{\pi \Gamma / 2} \tag{5}$$

with the Thomas-Reiche-Kuhn cross section given by

$$\sigma_{\text{TRK}} = \frac{60 N_P Z_P}{A_P} \text{MeVmb} \tag{6}$$

where N_P, Z_P, A_P are the neutron, proton and mass numbers of the projectile nucleus.

The theoretical description provided in equations (1) and (3) is able to provide a rough match between EM dissociation experiments and theory [12]. For much better agreement between theory and experiment, one must include a host of other corrections such as electric quadrupole effects [20, 21], Rutherford bending of the nuclear trajectories [14], uncertainties in experimental photonuclear cross sections [13], correct separation of Strong and EM cross sections in the original experiments [14] and higher order effects [13, 23]. When all these effects are included one obtains good agreement with experiment [14].

3   Nuclear Reactions for Space Radiation

From a space radiation point of view some of the most important projectile cosmic ray nuclei are C, Si and Fe. Some of the most important target (spacecraft shield) nuclei are C and Al. The most important energies are in the 1 - 10 GeV range. Using the methods described above and in the references [12, 13, 14, 15, 16, 20, 21, 22, 24, 25],

I have calculated both Electromagnetic and Strong interaction cross sections for single nucleon removal for a variety of projectiles and targets and energies. See Table 1.

Note that for light projectile-target combinations, such as a C projectile on a C target, the EM cross sections are very much smaller than the Strong interaction cross sections at all energies. Therefore neglecting EM processes here is a good approximation. For heavy projectile-target combinations, such as a Au projectile on an Fe target, the EM cross section is much bigger than the Strong interaction process and therefore the EM interaction cannot be neglected. The most important heavy ion reaction for space radiation is an Fe projectile cosmic ray nucleus impinging on an Al target (spacecraft). Depending on the energy the EM cross section ranges from about 30% to 50% of the Strong interaction cross section! (At 50 GeV/A the ratio is about 80%.) Therefore *Electromagnetic dissociation should not be neglected in space radiation transport codes.*

TABLE 1. Calculations of Single Neutron removal from the Projectile.

Projectile	Target	Tlab (GeV/A)	σ_{Strong} (mb)	σ_{EM} (mb)
^{12}C	^{12}C	3	64	0.6
		5	64	0.7
		10	64	0.9
		50	64	1.5
	^{27}Al	3	77	2.4
		5	77	3
		10	77	4
		50	77	6
	^{56}Fe	3	92	8.5
		5	92	11
		10	92	15
		50	92	25
^{28}Si	^{12}C	3	73	1.1
		5	73	1.4
		10	73	1.8
		50	73	3
	^{27}Al	3	86	5
		5	86	6
		10	86	8
		50	86	14
	^{56}Fe	3	100	17
		5	100	22
		10	100	30
		50	100	52
^{56}Fe	^{12}C	3	89	7
		5	89	8
		10	89	11
		50	89	17
	^{27}Al	3	102	27
		5	102	36
		10	102	47
		50	102	77
	^{56}Fe	3	116	104
		5	116	132
		10	116	178
		50	116	298

TABLE 1 continued

Projectile	Target	Tlab (GeV/A)	σ_{Strong} (mb)	σ_{EM} (mb)
^{197}Au	^{12}C	3	128	46
		5	128	56
		10	128	73
		50	128	118
	^{27}Al	3	141	201
		5	141	250
		10	141	330
		50	141	541
	^{56}Fe	3	156	749
		5	156	946
		10	156	1263
		50	156	2108

References

[1] International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Annals of the ICRP21. Elsevier Science, New York. (1991).

[2] National Council on Radiation Protection and Measurements. *Radiation Protection Guidance for Activities in Low-Earth Orbit.* NCRP Report No. 132 (2000).

[3] J.W. Wilson, L.W. Townsend, W. Schimmerling, G.S. Khandelwal, F. Khan, J.E. Nealy, F.A. Cucinotta, L.C. Simonsen, J.L. Shinn, and J.W. Norbury, *Transport Methods and Interactions for Space Radiations*, NASA Reference Publication 1257 (1991). Available at
http://techreports.larc.nasa.gov/ltrs/dublincore/1991/rdp1257.tex.html

[4] J.L. Shinn, S. John, R.K. Tripathi, J.W. Wilson, L.W. Townsend, and J.W. Norbury, *Fully Energy-Dependent HZETRN (A Galactic Cosmic-Ray Transport Code)*, NASA Technical Paper NASA TP-3243 (1992). Available at
http://techreports.larc.nasa.gov/ltrs/dublincore/1992/rdp3243.tex.html

[5] http://www.itn.mces.pt/ICRS-RPS/oralpdf/Wednesday12/Session17_1/TownsendO4.pdf

[6] http://www.fluka.org/

[7] http://wwwasd.web.cern.ch/wwwasd/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceMar

[8] L.W. Townsend, J.W. Wilson, R.K. Tripathi, J.W. Norbury, F.F. Badavi, and F. Khan. *HZEFRG1: An Energy-Dependent Semiempirical Nuclear Fragmentation Model.* NASA Technical Paper, NASA TP-3310 (1993). Available at http://techreports.larc.nasa.gov/ltrs/dublincore/1993/rdp3310.tex.html

[9] S.R. Blattnig, J.W. Norbury, R.B. Norman, J.W. Wilson, R.C. Singleterry, and R.K. Tripathi, *MESTRN: A Deterministic Meson-Muon Transport Code for Space Radiation*, NASA Technical Memorandum, NASA/TM-2004-212995. Available at http://techreports.larc.nasa.gov/ltrs/PDF/2004/tm/NASA-2004-tm212995.pdf

[10] J.W. Wilson, Health Physics **79**, 470 (2000).

[11] J.A. Simpson, Ann. Rev. Nucl. Part. Sci. **33**, 323 (1983).

[12] J.W. Norbury, Phys. Rev. C **40**, 2621 (1989).

[13] J.W. Norbury, Phys. Rev. C **47**, 406 (1993).

[14] J.W. Norbury and G. Baur, Phys. Rev. C **48**, 1915 (1993).

[15] J.W. Norbury, Phys. Rev. C **42**, 2259 (1990).

[16] J.W. Norbury and L.W. Townsend, Phys. Rev. C **42**, 1775 (1990).

[17] J.W. Norbury and L.W. Townsend, Astrophys. J. Suppl. **86**, 307 (1993).

[18] J.W. Norbury and C. Mueller, Astrophys. J. Suppl. **90**, 115 (1994).

[19] J.W. Norbury, F.A. Cucinotta, L. W. Townsend, and F.F. Badavi, Nucl. Instr. Meth. B **31**, 535 (1988).

[20] J.W. Norbury, Phys. Rev. C **41**, 372 (1990).

[21] J.W. Norbury, Phys. Rev. C **42**, 711 (1990).

[22] J.W. Norbury, Phys. Rev. C **45**, 3024 (1992).

[23] J.W. Norbury and M.L. Waldsmith, Phys. Rev. C **57**, 1525 (1998).

[24] J.W. Norbury, Phys. Rev. C **39**, 2472 (1989).

[25] R.T. Wheeler and J.W. Norbury, Phys. Rev. C **51**, 1566 (1995).

[26] J.W. Norbury, Phys. Rev. C **43**, R368 (1991).

[27] J.W. Norbury, Phys. Rev. D **42**, 3696 (1990).

[28] S.C. Ahern, J.W. Norbury, and W.J. Poyser, Phys. Rev. D **62**, 116001 (2000).

[29] S.C. Ahern and J.W. Norbury, Phys. Rev. D **68**, 113001 (2003).

[30] S.C. Ahern and J.W. Norbury, Phys. Rev. D **70**, 033008 (2004).

[31] C.A. Bertulani and G. Baur, Physics Reports **163**, 299 (1988).

[32] T.K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge University Press, New York, 1990.

[33] W.J. Llope and P. Braun-Munzinger, Phys. Rev. C **45** 799 (1992).

[34] C. Zeitlin, L. Heilbronn, J. Miller, S.E. Rademacher, T. Borak, T.R. Carter, K.A. Frankel, W. Schimmerling,, and C.E. Stronach, Phys. Rev. C **56**, 388 (1997).

[35] G.D. Westfall, L.W. Wilson, P.J. Lindstrom, H.J. Crawford, D.E. Greiner, and H.H. Heckman, Phys. Rev. C **19**, 1309 (1979).

[36] J.W. Wilson, L.W. Townsend, and F.F. Badavi, Nucl. Instr. Meth. Phys. Res. B **18**, 225 (1987).

[37] C. Brechtmann, W. Heinrich, and E.V. Benton, Phys. Rev. C **39**, 2222 (1989).

[38] T. Aumann et al, Z. Phys. A **352**, 163 (1995).

[39] J. Barrette et al, Phys. Rev. C **51**, 865 (1995).

[40] L.W. Townsend, J.E. Nealy, J.W. Wilson, and L.C. Simonsen, *Estimates of Galactic Cosmic Ray Shielding during Solar Minimum*, NASA Technical Memorandum, NASATM-4167 (1990).

[41] L.W. Townsend, F.A. Cucinotta, J.L. Shinn, and J.W. Wilson, *Effects of Fragmentation Parameter Variations on Estimates of Galactic Cosmic Ray Exposure*, NASA Technical Memorandum, NASA TM-4386 (1992). Available at
http://techreports.larc.nasa.gov/ltrs/dublincore/1992/rdp4386.tex.html

[42] J.W. Wilson, J. Miller, A. Konradi, and F.A. Cucinotta (eds.). *Shielding Strategies for Human Space Exploration*, NASA Conference Publication 3360 (1997).
See Chapter 1. Avalable at
http://techreports.larc.nasa.gov/ltrs/dublincore/1997/cp/NASA-97-cp3360.html

[43] G. Baur, K. Hencken, D. Trautmann, S. Typel, and H.H. Wolter, nucl-th/0008033.

[44] G. Baur, K. Hencken, D. Trautmann, S. Typel, and H.H. Wolter, nucl-th/0011061.

[45] J. Kiener, H.J. Gils, H. Rebel, S. Zagromski, G. Gsottschneider, N. Heide, H. Jelitto, J. Wentz, and G. Baur, Phys. Rev. C **44** 2195 (1991).

[46] B. David and S. Typel, Phys. Rev. C **68** 045802 (2003).

[47] B. Davids, S.M. Austin, D. Bazin, H. Esbensen, B.M. Sherrill, I.J. Thompson, and J.A. Tostevin, Phys. Rev. C **63** 065806 (2001).

[48] T. Motobayashi et al, Phys. Lett. B **264** 259 (1991).

[49] P. Banerjee and R. Shyam, nucl-th/0008025.

[50] R. Chatterjee and R. Shyam, Phys. Rev. C **66** 061601 (2002).

[51] J. Barrette et al, Phys. Rev. C **45**, 2427 (1992).

[52] R. Yanez et al, Phys. Rev. C **68** 011602 (2003).

[53] A. Grunschloss et al, Phys. Rev. C **60** 051601 (1999).

[54] D.L. Olson et al, Phys. Rev. C **44** 1862 (1991).

[55] T.D. Shoppa and S.E. Koonin, Phys. Rev. C **46** 382 (1992).

[56] F.A. Cucinotta, J.W. Wilson, T.K. Tripathi, and L.W. Townsend, Adv. Space Res. **22**, 533 (1998).

[57] M.B. Chadwick, P.G. Young, R.E. MacFarlane, M.C. White, and R.C. Little, Nucl. Sci. Eng. **144**, 157 (2003).

[58] M.C. White, R.C. Little, M.B. Chadwick, P.G. Young, and R.E. MacFarlane, Nucl. Sci. Eng. **144**, 174 (2003).